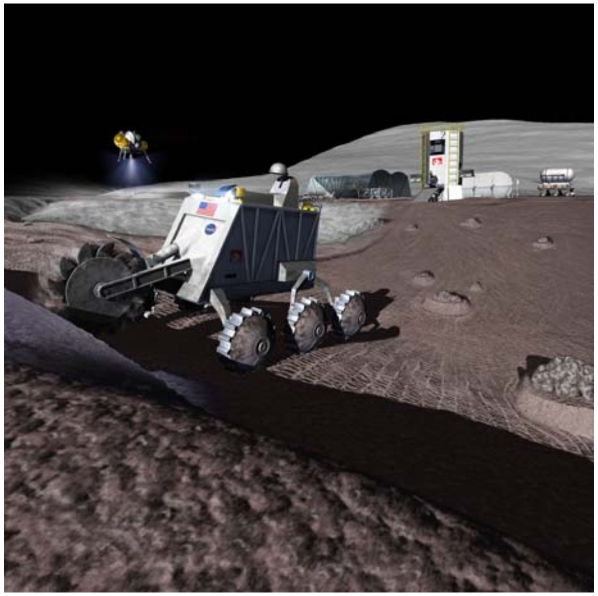
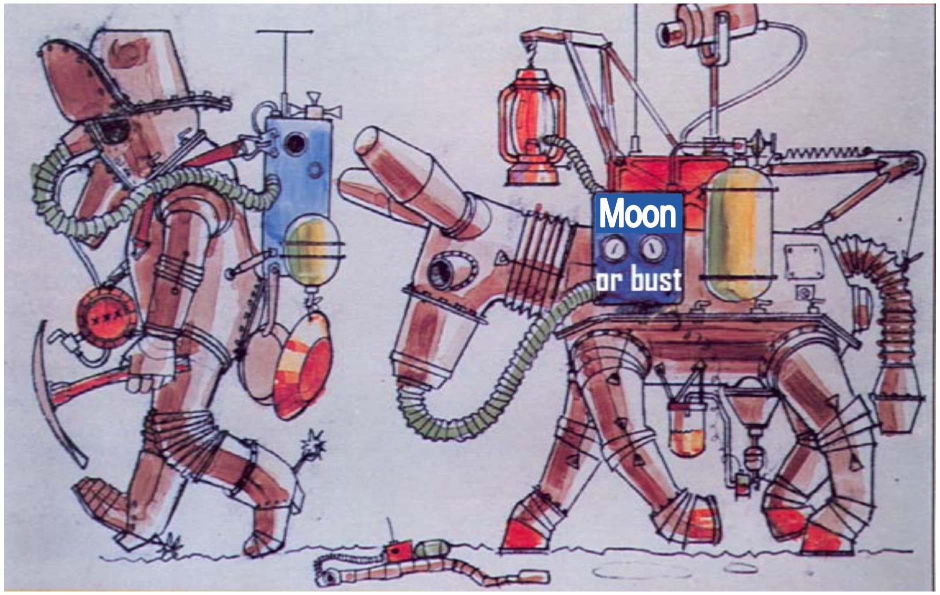
NASA
In-Situ Resource Utilization (ISRU) Research & Development





Jerry Sanders	JSC	gerald.b.sanders@nasa.gov
Bill Larson	KSC	william.e.larson@nasa.gov
Kurt Sacksteder	GRC	kurt.r.sacksteder@nasa.gov
Carole Mclemore	MSFC	carole.a.mclemore@nasa.gov
Ken Johnson	JPL	kenneth.r.johnson@jpl.nasa.gov

Lunar & Mars Resources

Moon Resources

Ilmenite - 15%
- $FeO \cdot TiO_2$ (98.5%)

Pyroxene - 50%
- $CaO \cdot SiO_2$ (36.7%)
- $MgO \cdot SiO_2$ (29.2%)
- $FeO \cdot SiO_2$ (17.6%)
- $Al_2O_3 \cdot SiO_2$ (9.6%)
- $TiO_2 \cdot SiO_2$ (6.9%)

Olivine - 15%
- $2MgO \cdot SiO_2$ (56.6%)
- $2FeO \cdot SiO_2$ (42.7%)

Anorthite - 20%
- $CaO \cdot Al_2O_3 \cdot SiO_2$ (97.7%)

Water (?)

1500 +/- 800 ppm Hydrogen at poles & permanent shadows

Solar Wind

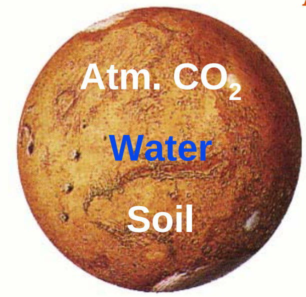
- Hydrogen (50 - 100 ppm)
- Carbon (100 - 150 ppm)
- Nitrogen (50 - 100 ppm)
- Helium (3 - 50 ppm)
- ^{3}He (4 - 20 ppb)

Mars Resources

Soil*

- Silicon Dioxide (43.5%)
- Iron Oxide (18.2%)
- Sulfur Trioxide (7.3%)
- Aluminum Oxide (7.3%)
- Magnesium Oxide (6.0%)
- Calcium Oxide (5.8%)
- Other (11.9%)
- Water (2 to >50%)[XX]

*Based on Viking Data
[XX]Mars Odyssey Data



Atmosphere

- Carbon Dioxide (95..5%)
- Nitrogen (2.7%)
- Argon (1.6%)
- Oxygen (0.1%)
- Water (210 ppm)

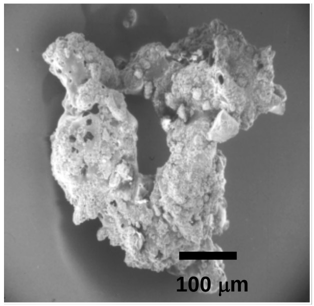
Lunar Resources

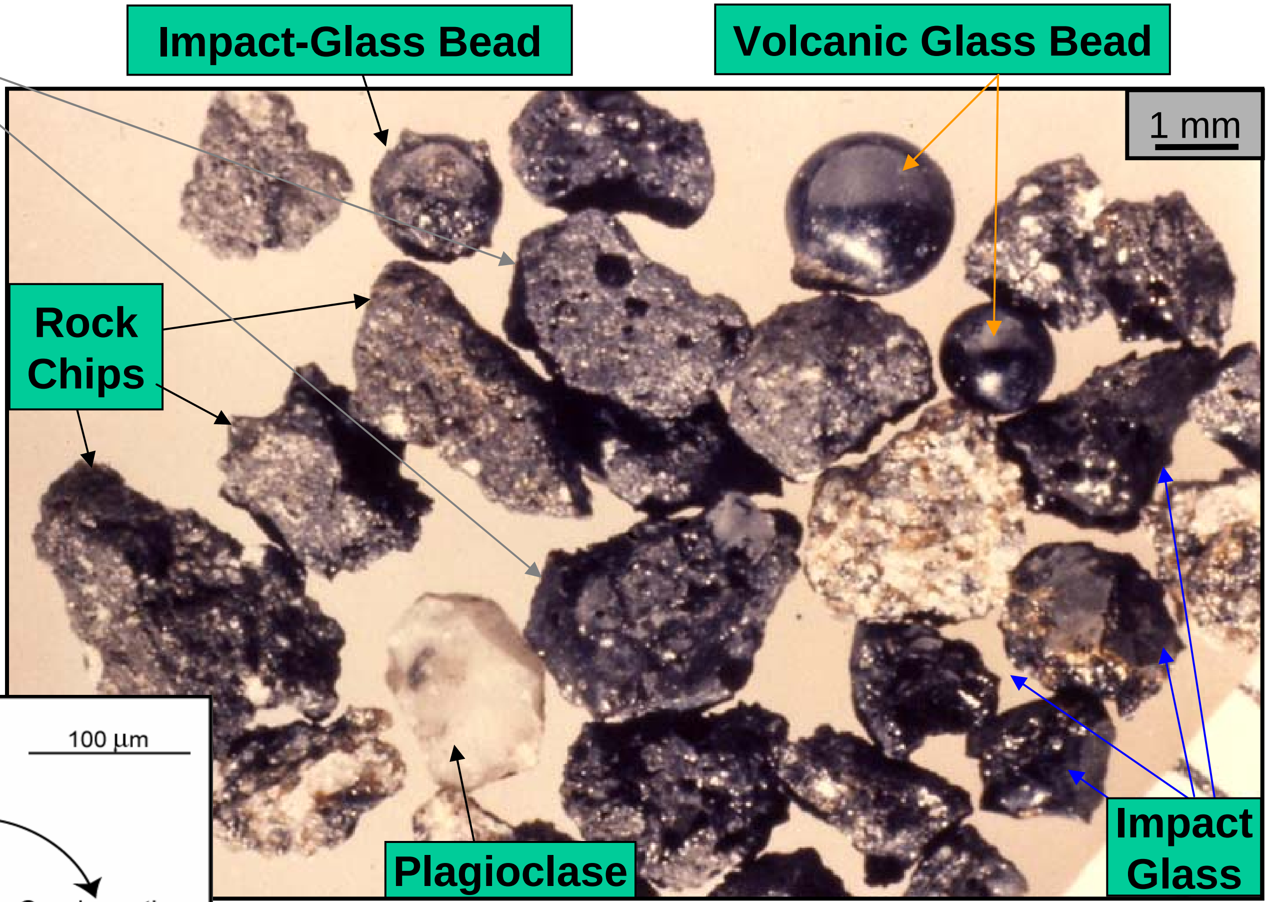
- Oxygen is the most abundant element on the Moon
- Solar wind deposited volatile elements are available at low concentrations
- Metals and silicon are abundant
- Lunar resources are understood at a global level (>30 km pixel with Apollo point references) except for permanently shadowed craters and ***possibility of water/ice***

Mars Resources

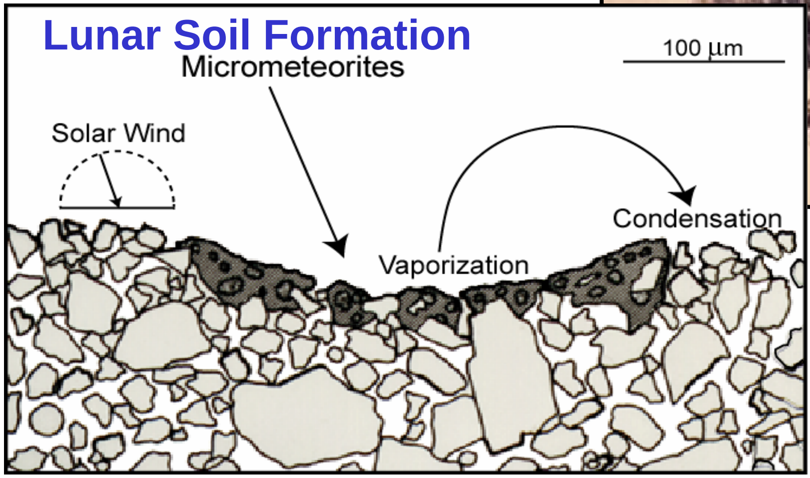
- Atmospheric gases, and in particular carbon dioxide, are available everywhere at 6 to 10 torr (0.1 psi)
- Viking and Mars Odyssey data shows that water is wide spread but spatial ***distribution and form of water/ice is not well understood*** (hydrated clays and salts, permafrost, liquid aquifers, and/or dirty ice)

Lunar Mare Soil





Agglutinate: Pieces of minerals, rocklets, and glass welded together by shock-melt glass



Comminution, Agglutination, & Vapor Deposition

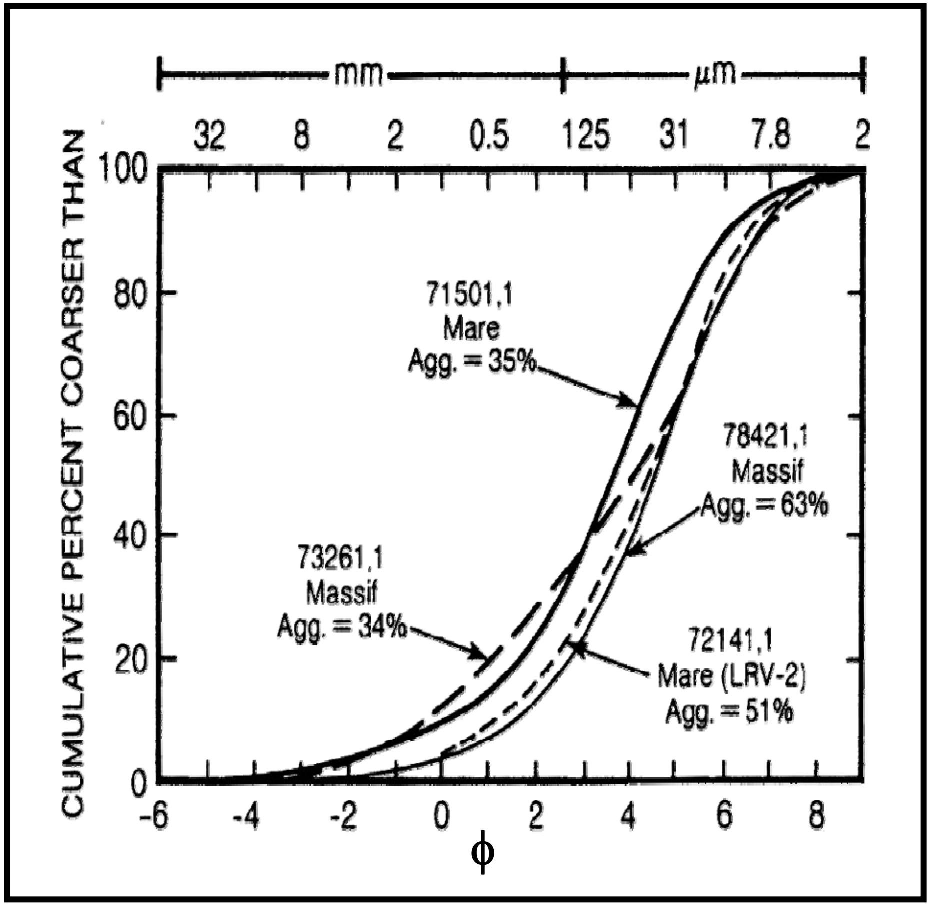
Regolith: broken up rock material
Soil: <1 cm portion of the Regolith
Dust: < 50 µm portion of the Soil

- **The bulk of lunar soil is <1 mm in size**

Courtesy Dr. Larry Taylor, Univ. of Tennessee

The bulk of lunar soil is <1 mm in size

Particle Size Distribution



Distribution of particle sizes in separate splits of Apollo 17 soil 78221,8,

Particle Weight Distribution

Soil	Size Fraction					Mean Size, M_z	
	>1 cm	4-10 mm	2-4 mm	1-2 mm	<1 mm	<1cm	<1mm
	(weights in grams)					(mm)	(mm)
14163	0.0	196.5	197.1	288.7	4444.0	76	56
15220	0.0	7.0	5.8	2.4	290.0	-	43
68500	1.3	17.3	25.1	37.8	521.1	106	68
72140	1.3	2.7	1.9	5.3	225.9	57	50
72500	3.1	8.0	12.9	24.1	687.2	67	57
73240	1.6	22.3	14.4	14.9	192.7	127	51
74220**	0.0	0.98	0.17	0.68	7.77	-	41
78220	0.0	1.5	2.7	5.2	227.1	50	45

Weight distribution in size fractions of scooped surface soils.

Courtesy Dr. Larry Taylor, Univ. of Tennessee

Lunar Soil Properties

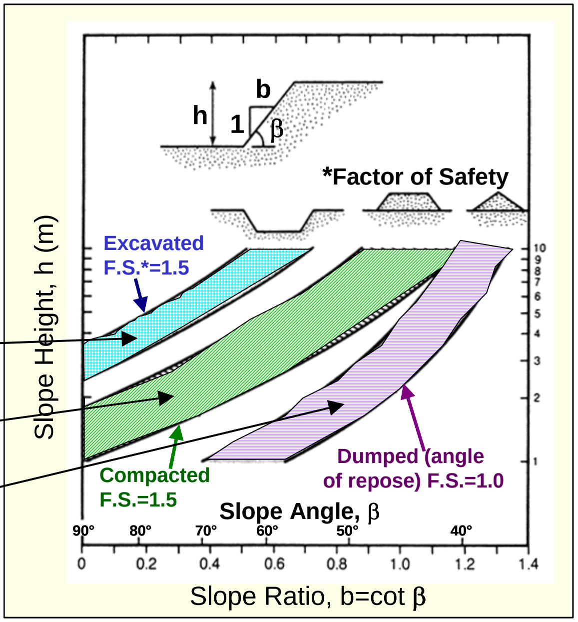
Specific Gravity: Range from 2.3 to >3.2; recommend 3.1 for Engineering use.

Bulk Density:
top 15 cm = 1.45-1.55 g/cm3; avg = 1.50 ±0.05 g/cm3
0-30 cm = 1.53-1.63 g/cm3; avg = 1.58 ±0.05 g/cm3
30-60 cm = 1.69-1.79 g/cm3; avg = 1.74 ±0.05 g/cm3
0-60 cm = 1.61-1.71 ±0.05 g/cm3; avg = 1.66 ±0.05 g/cm3
values up to 1.9 g/cm3 estimated at depth of cores to 2.98 m

Slope Stability

Calculated stability of artificial slopes constructed in lunar surface material. Data are presented for 3 situations:

(1) an excavation in lunar soil
(2) a compacted pile of excavated lunar soil
(3) a dumped pile of lunar soil



A vertical cut can safely be made in lunar soil to a depth of about 3 m; an excavated slope of 60° can be maintained to a depth of about 10 m.

Soil Porosity

Depth Range (cm)	Average Porosity n, (%)	Average Void Ratio, e
0-15	52 ± 2	1.07 ± 0.07
0-30	49 ± 2	0.96 ± 0.07
30-60	44 ± 2	0.78 ± 0.07
0-60	46 ± 2	0.87 ± 0.07

Lunar soil, in-situ, is very dense, more than that which could be produced with mechanical compaction equipment

– the lunar soil has experienced slow shaking over eons of time.

Courtesy Dr. Larry Taylor, Univ. of Tennessee

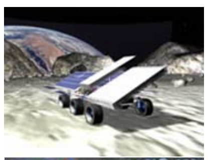
Objectives of Lunar ISRU Development & Use

- **Identify and characterize resources on Moon** (especially polar region) that:
  - Can strongly influence mission phases, locations, and element designs to achieve maximum benefit of ISRU
  - Is synergistic with Science and space commercialization objectives
- **Demonstrate ISRU** concepts, technologies, & hardware that reduce the mass, cost, & risk **for future Mars missions**
  - Excavation and material handling & transport
  - Volatile/hydrogen/water extraction
  - Thermal/chemical processing subsystems for oxygen and fuel production
  - Cryogenic fluid storage & transfer
  - Metal extraction and fabrication of spare parts
- **Use Moon for operational experience** and mission validation **for Mars**
  - Pre-deployment & activation of ISRU assets
  - Making and transferring mission consumables *(propellants, life support, power, etc.)*
  - Landing crew with pre-positioned return vehicle or 'empty' tanks
  - 'Short' (<90 days) and 'Long' (300 to 500 days) Mars surface stay dress rehearsals
- **Develop** and evolve lunar **ISRU capabilities** that *enable* exploration capabilities **from the start of the Outpost** phase
  - ex. Human and robotic hoppers for long-range surface mobility and global science access; power-rich distributed systems; enhanced radiation shielding, etc.
- **Develop** and evolve lunar **ISRU capabilities** to support sustained, **economical space transportation**, presence on Moon, **and space commercialization** efforts
  - Lower Earth-to-Orbit launch needs
  - Enable reuse of transportation assets and single stage lander/ascent vehicles
  - ➢ Lower cost to government thru government-commercial space commercialization initiatives

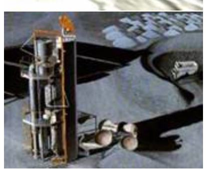
ISRU for Human Lunar Exploration

- **Capabilities**

  - **Pre-Outpost**
    - Determine type, amount, and location of possible resources of interest (i.e. ilmenite, water, etc.) – link to Science objectives if possible
    - Perform proof-of-concept and risk reduction demonstrations to certify ISRU capabilities for use at the Outpost- link to commercialization of space if possible)
    - Perform site characterization of topography and subsurface
    - Perform pre-Outpost preparation (i.e. landing plume berms, landing area clearance, hole or trench for habitat or nuclear reactor, etc.)



  - **Initial ISRU Capabilities at Start of Outpost:**
    - Excavation for oxygen production, reactor placement, radiation & plume shielding
    - Pilot-scale oxygen production, storage, & transfer capability
    - Hydrogen/fuel production based on results of RLEP and Sortie missions to lunar poles
    - ISRU produced oxygen ready for 2nd Outpost crew return vehicle

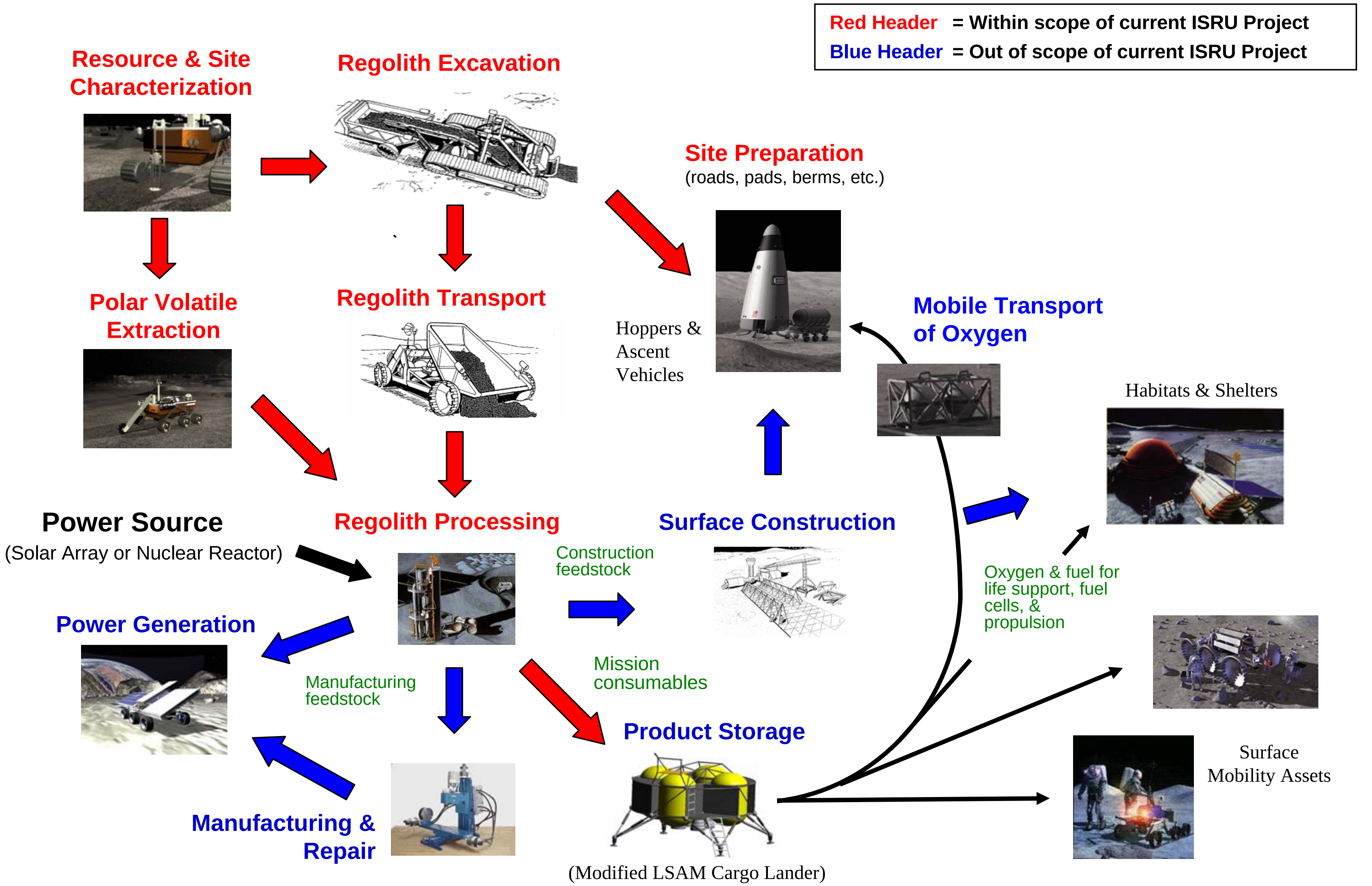


  - Mid-Term ISRU Capabilities
    - In-situ fabrication and repair
    - In-situ power generation
    - Thermal energy storage & use
    - Increased oxygen/fuel production to enable completely reusable landers or surface hoppers

  - Long-Term Lunar Capabilities
    - In-situ manufacturing and assembly of complex parts and equipment
    - Habitat and infrastructure construction (surface & subsurface)
    - In-situ life support – bio support (soil, fertilizers, etc.)
    - Power generation for beyond Moon: beaming, elium-3 isotope (^{3}He) mining, etc.

Gerald. B Sanders/JSC, gerald.b.sanders@nasa.gov

ISRU Surface Elements & Activities



Current Lunar ISRU Mass & Power Estimates
(Oxygen extraction from regolith)

Oxygen production rate of 8 to 10 MT per year is baselined for start of Outpost phase:

- **Supports oxygen need for two ascent vehicles (3500 kg each) and life support/EVA oxygen for complete year (permanent crew of 4)**

- Oxygen production plant mass and power estimates
  - Eagle Engineering report: Hydrogen reduction of ilmenite: 800 kg and 15 KW of power; 36.5 kg/hr regolith excavation
  - Orbitec: Carbothermal reduction of regolith: **450 kg & 13.5 KW power**; 15 kg/hr regolith
  - Boeing: Molten electrolysis of regolith: 550 kg & 66 KW; 12.5 kg/hr regolith

- Regolith excavation system estimates
  - Excavation unit mass of 600 kg based on old Eagle Engineering report and requirement to also support berm and trench construction for nuclear reactor and landing debris protection.
  - Excavation unit re-evaluated based on bucket wheel excavation work performed by Colorado School of Mines and Northern Centre for Advanced Technology (NORCAT)
    - Laboratory tests showed high excavation rates up to 150 kg/hr for small vehicle (<50 kg)
    - Order of magnitude higher excavation rate capability above processing feed rate easily covers extra time required for traverse and maintenance
    - Flight vehicle estimated in the **100 to 150 kg range** to ensure excavation stability, support hardware allocations, and on-board power system even though excavation rate is greater than required

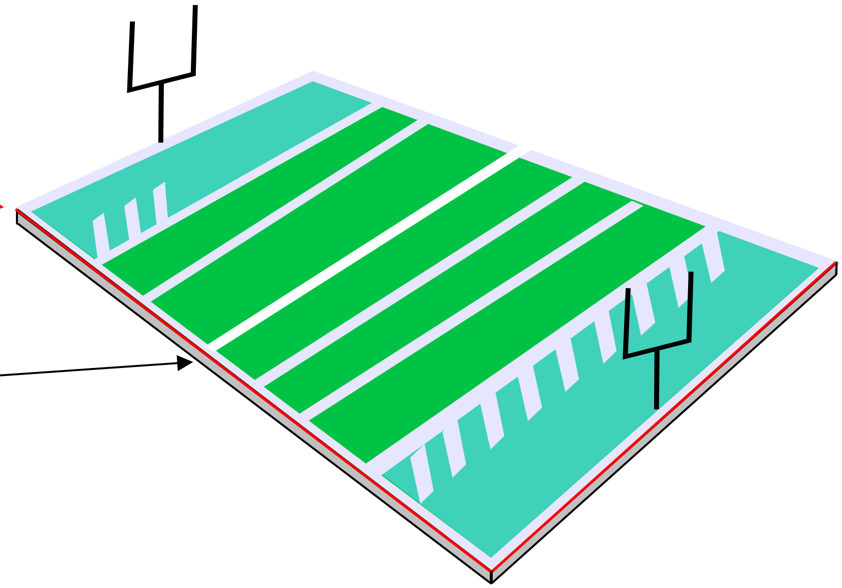
Mass of ISRU hardware required to produce 8 to 10 MT of oxygen per year is <1000 kg.

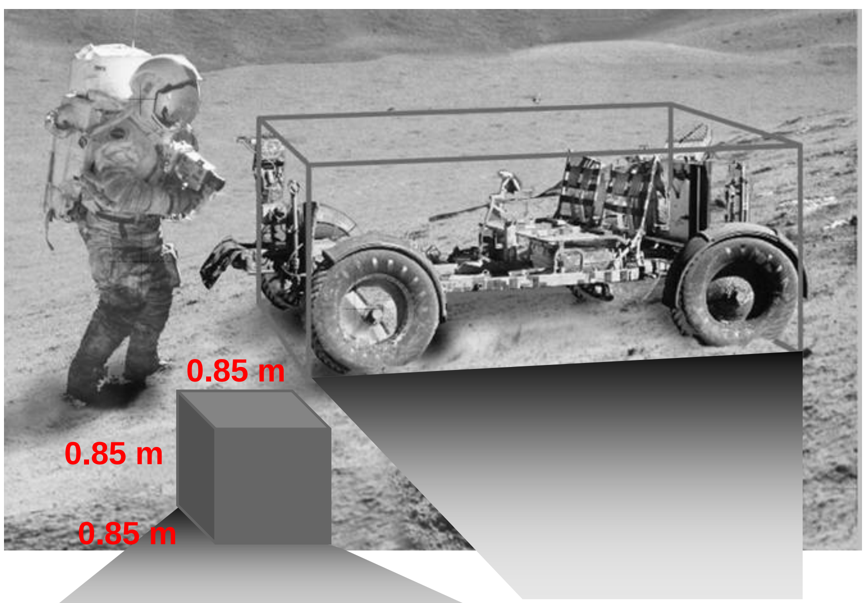
- Multiple excavation units
- Mass of power and oxygen storage and transfer system not included

ISRU Analogies

8 MT of oxygen per year requires excavation of a football field (with end zones) to a depth of 0.7 to 2 cm**!** (like cutting the grass)

300 MT of oxygen per year requires excavation of a football field (with end zones) to a depth of 27 to 75 cm**!**

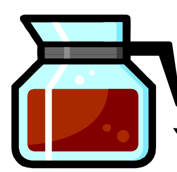




Volume equivalent to 1 Metric Ton of lunar regolith

Volume equivalent to 20 Metric Tons of lunar regolith

8 MT of oxygen per year requires a regolith excavation rate of ~**1 cup per minute!**
(5% efficiency - 50% time-14 day lunar day/night)



300 MT of oxygen per year requires a regolith excavation rate of ~**10 cups per minute**!
(14% efficiency - 70% time-polar region)

Regolith Excavation & Material Handling

Scope: Lunar regolith excavation and material handling for oxygen production, volatile extraction (including in permanently shadowed craters), and surface preparation and construction

Excavation for Volatiles

Design drivers for lunar regolith excavation & mat'l handling:

- Excavation for oxygen production
- Excavation for surface preparation and construction (including nuclear reactor placement/shielding)
- Excavation for volatile extraction (especially for polar hydrogen/water)

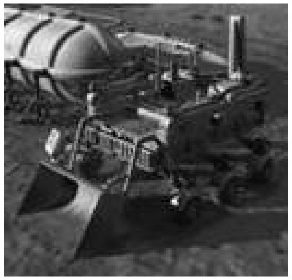
Polar Mining for Water

Currently Funded & Planned Activities

- Excavation analytical tools & methods
  - Granular physics & low-g motion modeling & laboratory work
  - Regolith property and excavation technique evaluation and testing

Excavation for O_2 production

- Excavation requirements & trade studies
  - Integrated excavation/material transport vs separate vehicles
  - Optimum number and size of excavation vehicles
  - Commonality vs optimized design of surface mobility assets
  - Nuclear reactor burial/shielding impacts on ISRU capabilities



Excavation for construction

Regolith Excavation & Material Handling (Cont.)

Currently Funded & Planned Activities (Cont.)

- Excavation hardware development, testing, and demonstrations.
- Material transportation and sizing to and removal from processing unit.
  - Joint development with Oxygen Production and Volatile Extraction
- Joint development activities:
  - Surface Mobility (Human/Robotic Interface, Power, Autonomous Control/multi-vehicle coordination)
  - Low-temperature mechanisms & dust mitigation

Excavation Development & Operation Challenges & Risks

- Understanding the low-g particle and material behavior impact on lunar excavation and material transport
- Developing dust tolerant sliding actuators for regolith excavation
- Developing dust tolerant rotating motors/actuators for regolith excavation and transfer
- Understanding the effect of high subsurface regolith density on excavation force/power and designs
- Minimizing losses of solar wind implanted volatiles during excavation
- Gaining a better knowledge of the level of maintenance required

Oxygen Production from Regolith

Scope: Chemically, electrically, and/or thermally extracting oxygen from the metal and non-metal compounds in lunar regolith. Includes regolith pre-processing and beneficiation.

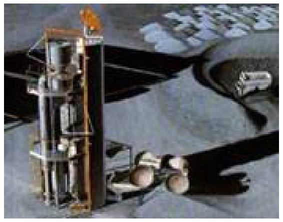
Design drivers for oxygen production from lunar regolith processing:

- 1 to 2 MT O_2/yr for life support, 8 MT O_2/yr for ascent propulsion
- Other resources of interest, such as silicon, iron, titanium, aluminum, etc. may also be processed in the future based on technologies developed for oxygen production.

Sortie O_2 production demo

Currently Funded & Planned Activities

- Oxygen production from regolith process modeling and trade studies
- 'Proof-of-Concept'-Scale Oxygen Production System Development
  - Hydrogen reduction of regolith (RESOLVE)
  - Also evaluated applicability of carbothermal reduction, molten salt, and molten electrolysis processes
- 'Risk Reduction'-Scale Oxygen Production System Development
  - Hydrogen reduction of regolith (PILOT contract)
  - Methane-based carbo-thermal reduction of regolith (PILOT Contract)
  - Carbon monoxide-based carbo-thermal reduction of regolith (Joint SBIR)
  - Regolith electrolysis processes



Large-scale Outpost O_2 production plant

Oxygen Production from Regolith (Cont.)

Currently Funded & Planned Activities (Cont.)

- Regolith beneficiation and pre-processing
- Emphasize development of common technologies/subsystems
  - Life support & EVA
  - Mars atmospheric and fuel production technologies
  - Sealing & dust mitigation
  - Power/thermal management and transfer (microwave, solar, resistive)

Oxygen Production Development and Operation Challenges & Risks

- Developing sealing mechanism for regolith inlet and outlet from processing chamber that eliminate/minimize gas losses
- Developing techniques to eliminate/mitigate dust impact on solar collectors and transmission windows for regolith processing
- Identifying/demonstrating regolith processing chamber materials for high temperature/molten regolith processing chambers
- Removing molten or solidified spent regolith from processing chambers
- Developing long-duration, non-eroding, oxygen compatible electrodes
- Removing and regenerating salts for electrolysis from spent regolith
- Process start-up/shutdown or thermal management during lunar night for non-nuclear power scenarios
- Developing highly reliable, autonomous calibration control hardware (sensors, flowmeters, etc.)
- Develop technologies to cover plastic trash and bio-material into usable products

Polar Volatile Collection & Separation

Scope: All aspects of locating and characterizing lunar volatile resources; thermal, chemical, and/or electrical processing this regolith to release volatiles; identifying/quantifying all volatiles; and separating and collecting volatiles of interest. Also includes:

- Prospecting, resource mapping, and resource extraction operation planning for all potential resources of interest
- Site surveying for Habitat placement and Outpost planning and construction activities

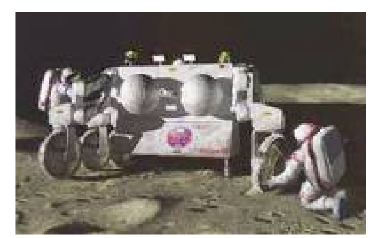
Design drivers for polar volatile resource extraction, collection, and separation:

- Operation in high vacuum, 40 to 100 K temperature environment
- Unknown regolith/resource characteristics
- Unknown terrain features and crater ingress/egress

Polar volatile characterization

Currently Funded and Planned Activities

- 'Proof-of-Concept'-Scale Volatile Extraction System Development: Regolith and Environment Science & Oxygen and Lunar Volatile Extraction (RESOLVE)
  - 1 meter core sample drill, crusher, and sample transfer unit
  - Volatile chamber with gas chromatograph (mass spec)
  - Water and hydrogen separation and capture and water electrolysis
  - Possible payload for RLEP2/LPRP mission
  - 30 to 50 kg mass and <100 Watts power



Outpost polar volatile plant

Polar Volatile Collection & Separation (Cont.)

Currently Funded and Planned Activities (Cont.)

- 'Risk Reduction'-Scale Volatile Extraction System Development
  - Excavation requirements & modeling
  - Prospecting tools and instruments – Resource Mapping
- Emphasize joint development activities
  - Low-temperature mechanisms & dust mitigation
  - Science instruments and sample collection hardware for resource assessment

Polar Volatile Development and Operation Challenges & Risks

- Mechanical system operation in 40K environment (lubricants, sliding surfaces, motors, etc.)
- Addressing the impact of unknown regolith material and resource characteristics on designs and operations
- Collecting and separating possible water, hydrogen, and other volatile 'resources' of interest (methane, ammonia, hydrocarbons, etc.)

Past & Current ISRU work Academia*

- **Texas A&M** - KC-135 lunar excavation force testing
- **Colorado School of Mines** – ISRU system & economical modeling; Excavation concepts; Buckwheel excavator design testing
- **Univ. of Missouri, Rolla** – Excavation studies; polar regolith/water simulation
- **Univ. of Houston** – In-situ solar array production
- **Univ. of Tenn.** – Lunar regolith expertise; microwave heating of regolith
- **Univ. of Hawaii** – Lunar regolith expertise; polar water property characterization
- **Old Dominion Univ.** – Carbon dioxide electrolysis for Mars ISRU
- **Univ. of Arizona** – Carbon dioxide electrolysis for Mars ISRU
- **Univ. of Washington** – Mars atmospheric water collection
- **Florida Institute of Technology** – Salt and molten electrolysis of regolith
- **Mass. Institute of Technology** – Salt and molten electrolysis of regolith
- **International Space Univ.** – ISRU engineering & economic modeling study

***Does not include past work in micro-gravity program or current surface mobility development applicable to ISRU**

Current Lunar ISRU Development Participants

- **JSC – Project & Polar Volatile Lead**
  - ISRU management and system modeling
  - Regolith & Environmental Science and Oxygen & Lunar Volatile Extraction (RESOLVE)
  - Hydrogen reduction oxygen extraction from regolith design and laboratory testing
  - Lunar material science & handling
  - Lunar simulant development support
  - Regolith material transport support
  - ISRU Small Business Innovative Research (SBIR) subtopic lead
- **KSC – Oxygen Production Lead**
  - Regolith electrolysis oxygen production modeling and laboratory testing
  - Lunar regolith excavation modeling and development support
  - RESOLVE – sample collection, volatile chamber, and water/hydrogen collection and processing
  - Launch support infrastructure
  - ISRU SBIR subtopic support
- **MSFC – Simulant Development Lead**
  - Lunar simulant development
  - Oxygen extraction from regolith
  - ISRU SBIR subtopic support
- **GRC – Excavation & Transport Lead**
  - Lunar-g particle and material behavior modeling
  - Regolith excavation and material transport modeling and laboratory testing
  - Oxygen extraction from regolith modeling
  - RESOLVE participant
  - KC-135, drop tower, & micro-g testing
  - ISRU SBIR subtopic support
- **JPL – Instrument & Resource Prospecting Lead**
  - System modeling
  - RESOLVE – regolith chemical and physical characterization; regolith thermal probe
  - In-situ instruments and sensors for resource and site assessment
- **ARC – New in FY07**
  - Mars science drilling and subsurface exploration expertise
  - Resource prospecting instrumentation and mapping hardware and software support
  - Rover/arm integration and operations with ISRU